
3J
2E
70

Sailors aboard the USS Ronald Reagan *scrub the aircraft carrier's flight deck to remove potential radiation contamination from the Fukushima Daiichi nuclear power plant meltdown. The* Ronald Reagan *provided humanitarian assistance to Japan following the March 2011 earthquake and tsunami.* *(Photo: U.S. Navy)*

FIXING FUKUSHIMA

Los Alamos's muon vision to the rescue.

On the afternoon of March 11, 2011, a 9.0-magnitude earthquake occurred off Japan's northeast coast. About 50 minutes after the quake, a 45-foot-high tsunami slammed into the Japanese coastline. More than 18,000 people were killed, 300,000 were evacuated, and entire communities were destroyed.

And as if two natural disasters in less than an hour weren't devastating enough, the quake initiated the meltdown of three reactors at the Fukushima Daiichi nuclear power plant. A plan for locating and removing the melted fuel is just now coming to fruition—thanks to a technology developed by Los Alamos scientists.

Japan's Fukushima Daiichi nuclear power plant before the March 2011 earthquake and tsunami. *(Photo: TEPCO)*

These photos showing the extensive damage at Fukushima were taken less than a week after the tsunami of March 11, 2011. Left: Conditions around Reactors 5 and 6. Right: The Reactor 3 building after an explosion blew off its upper floors. The explosion was triggered by the ignition of hydrogen gas created by reactor fuel overheating. Reactor buildings 1 and 4 suffered similar explosions in the days immediately following the tsunami. (Photos: TEPCO)

The quake initiated Fukushima's automatic reactor shutdown. It also cut off the reactor complex from the electric power grid. However, the tsunami that followed overwhelmed the 30-foot-high seawall that Japanese experts believed would protect Fukushima, swamped the lower floors of the reactor buildings with 15 feet of water, and permanently knocked out the reactors' emergency electric generators—and with them, their cooling-water circulation pumps. The reactors' cores containing hot nuclear fuel lost critical cooling and some (perhaps all) of the fuel became so hot it melted. Life-threatening radiation was released.

Now, more than five years later, radiation levels inside the buildings that contained the melted fuel are still lethal. The deadly fuel must be removed, but key questions still need definitive answers. Before the process of fuel removal can begin, the exact status of the fuel must be known. How much has melted? Where is it? The Japanese government, nuclear engineers, and plant operators will not have the answers until they can see inside the reactors. Yet without technology that allows them to proceed safely, the Japanese cannot begin the process.

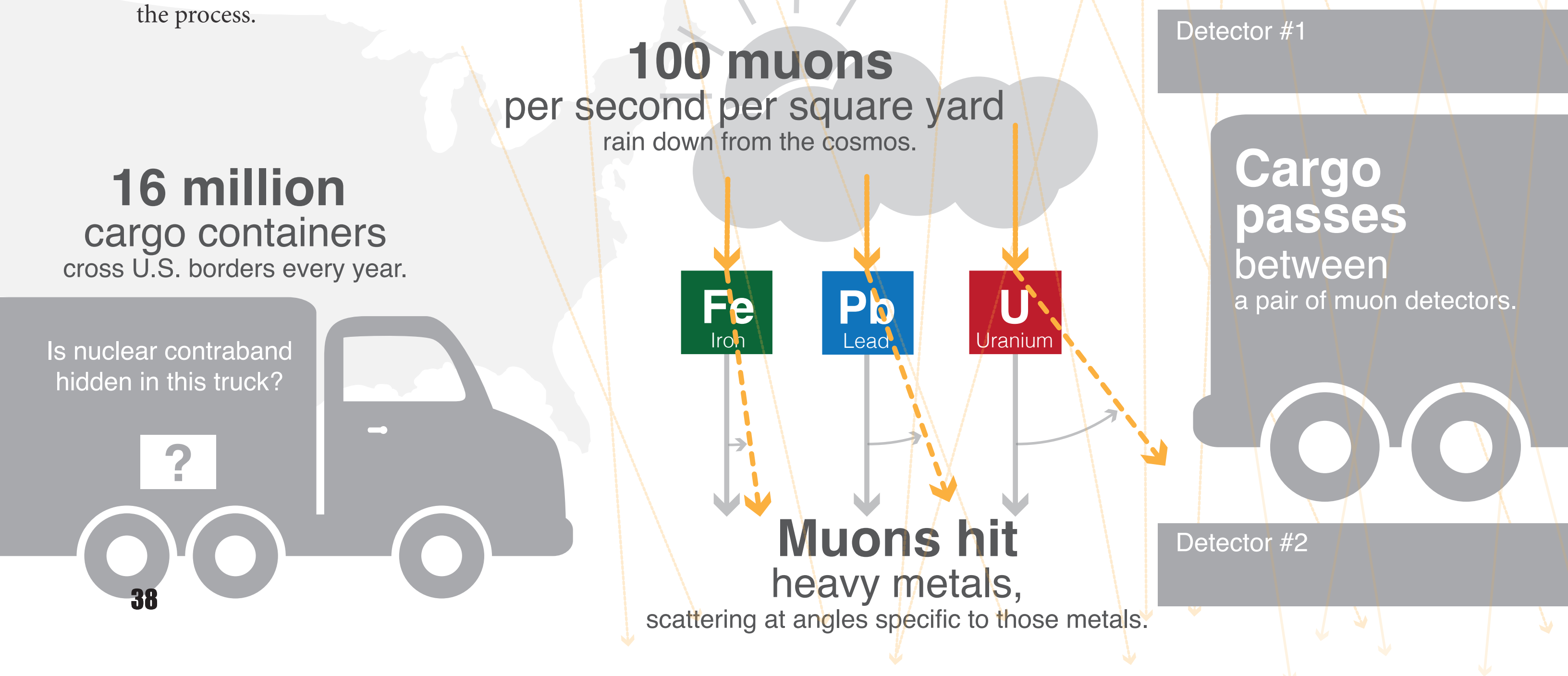
Before the process of fuel removal can begin, the exact status of the fuel must be known.

Muon vision

That's where Los Alamos National Laboratory comes in. Los Alamos scientists have created a new type of penetrating "vision" that can detect nuclear materials, such as uranium and plutonium, hidden inside very thick layers of concrete and steel. This so-called muon vision (see "What is Muon Vision?" page 39) uses cosmic ray muons, which are always present and which, unlike x-rays, are harmless to humans.

Muon vision has already been commercialized. Los Alamos and California-based Decision Sciences International Corporation (DSIC) have worked together to create a unique

(continued on page 40)



What Is Muon Vision?

Muons are subatomic particles created when very high-energy cosmic-ray particles from outer space collide with atomic nuclei in the upper layers of the Earth's atmosphere. Once created, muons travel at nearly the speed of light and rain down on the Earth's surface from random locations and in random directions; every second, 100 muons hit each square yard of the Earth's surface. Their tremendous energy enables them to penetrate most objects and even travel hundreds of feet into the Earth's crust. Yet, muons compose fewer than 10 percent of all background radiation and are harmless to people.

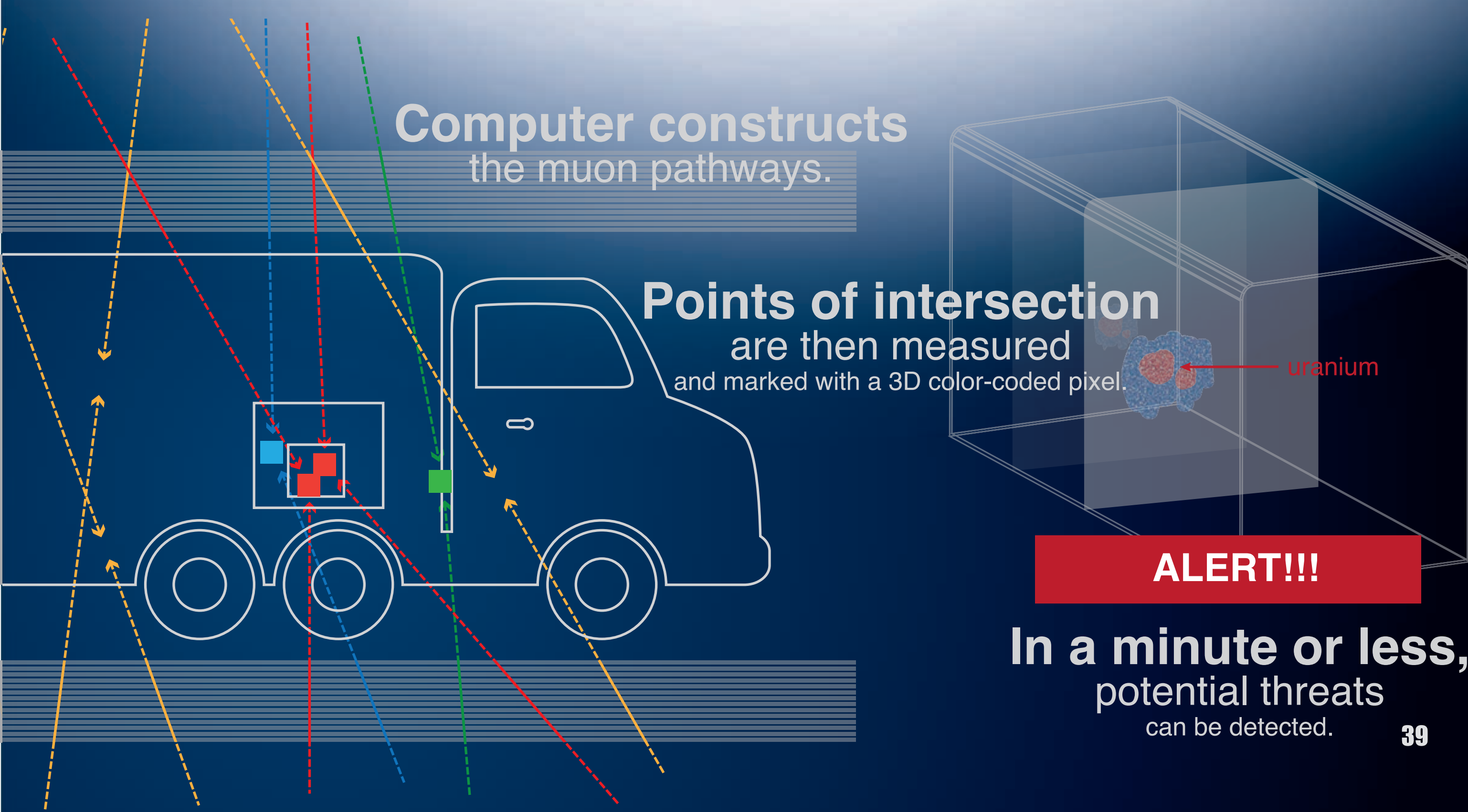
Muons continuously scatter as they move through material; they scatter more in very heavy materials than in lighter materials. Uranium and plutonium, which are heavy, cause the largest scattering angles, albeit no more than a few degrees. Lighter elements, such as iron, cause smaller angles, and even-lighter elements, such as oxygen, cause little or no scattering. So, measuring the scattering angle reveals the identity of the material that caused the scattering. Just as important, the angle also reveals the location of the material. In that way, muons can be used to "see" materials deep inside closed containers . . . or inside damaged reactors.

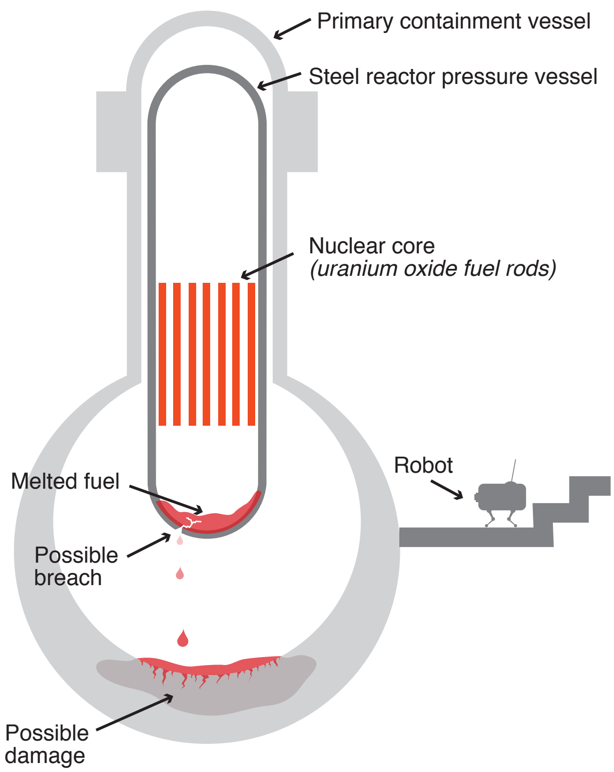
Los Alamos's unique muon vision measures muon scattering and "sees" materials otherwise hidden from view. To interrogate the inside of a shipping container, Decision Sciences International Corporation (DSIC) has commercialized muon vision. DSIC uses two specially designed detectors placed above and below the container. The system records a muon's path through the top detector (before it enters the container) and then measures its path through the bottom detector (after it exits the container).

Highly sophisticated software then traces the entry and exit paths back to where they meet inside the container—the point of intersection is the location of a material. If the lines meet at a very slight angle, the muon struck a lighter element. If the lines meet at a larger angle, the muon struck a heavy material.

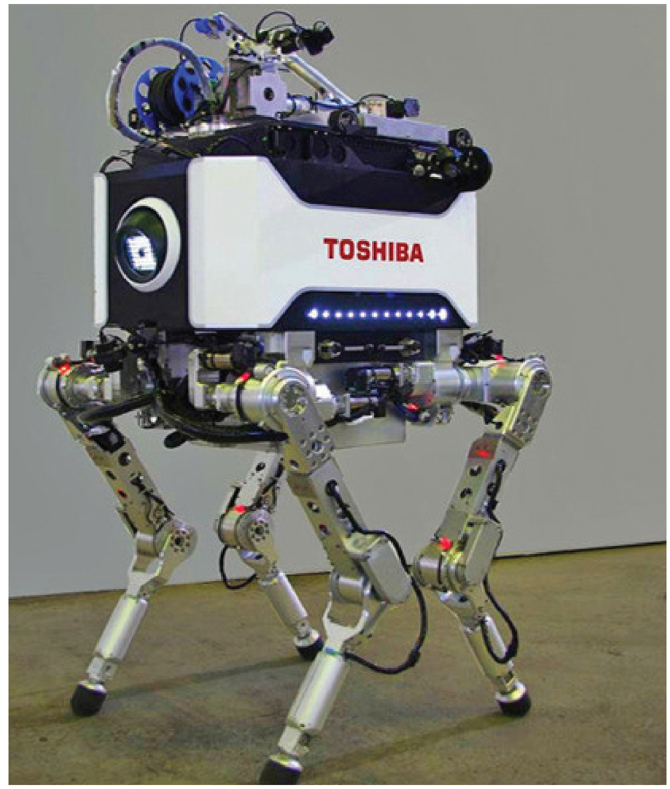
By detecting enough scattered muons, the computer software can also identify the shape of the heavy material—a particularly important feature if a material has melted. The software can even translate the data into a real-time, 3D digital image, color-coded to indicate different heavy materials. As shown in the infographic below, a lead box can be differentiated from smuggled uranium within it and from the sacks of cement that surround it inside a shipping container.

~Necia Grant Cooper





After melting—partially or completely—did nuclear fuel (red) sink to the bottom of the steel pressure vessel and cool? Or did it melt through the steel pressure vessel onto the floor of the reactor's primary containment vessel (PCV)? Or possibly even eat into the PCV's very thick concrete base? Once muon vision locates the fuel, robots could enter to assess the cleanup challenges ahead.



Toshiba has developed a unique tetrapod robot able to carry out investigative and recovery work inside the damaged reactor buildings at Fukushima—locations too dangerous for people to enter. The remote-controlled robot integrates cameras and a dosimeter (radiation monitor) to investigate the conditions inside the reactors. The multiple joints of its legs enable the robot to walk on uneven surfaces, avoid obstacles, and climb stairs to access areas that wheeled or tracked robots cannot. (Photo: Toshiba)

muon vision system to scan cargo containers and trucks at ports and border crossings for concealed uranium and plutonium (see "Muon Vision for U.S. National Security," page 46). Now Los Alamos and DSIC are partnering with Tokyo-based Toshiba Power Systems Company to use muon vision to safely investigate the Fukushima reactors. If the technology works on this large-scale application—and muon vision inventor Chris Morris, a physicist at the Los Alamos Neutron Science Center, believes it will—muon vision could reduce the time it takes the Japanese to clean up the site by 10 years.

The core of the problem

The cleanup efforts are daunting. Tokyo Electric Power Company (TEPCO), which operates the plant, expects the work to take 30 to 40 years without using muon vision and cost at least $8 billion. (In comparison, cleanup of the much smaller accident at Pennsylvania's Three Mile Island in 1979 cost $1 billion and lasted 14 years.) If the exact locations of the fuel can be learned, not only a decade but possibly billions of dollars might be saved. But first, specific questions must be answered: What fraction of the fuel rods is still intact in the pressure vessels? Has any fuel melted to the bottom of a pressure vessel? Has a pressure vessel been breached, and has fuel reached the bottom of the surrounding containment vessel?

> **The fuel in Reactor 1 likely melted through the pressure vessel to the bottom of the containment vessel.**

Currently, experts suspect that all the fuel in Reactor 1 melted, burned its way through the pressure vessel, and now sits at the bottom of the containment vessel, possibly eating into the concrete base. (See illustration.) The fuel in Reactors 2 and 3 might be distributed between their cores and the pressure and containment vessels.

But the trouble is that the location of the fuel is not really known. Each possible scenario would require a different cleanup strategy. Fuel rods that are intact might be pulled out and removed using one strategy. If fuel rods have melted but are still inside the pressure vessel, another strategy might be to remove the entire vessel. Fuel that has melted through the pressure vessel will require some other removal strategy. A breached containment vessel will require still another strategy. None of these cleanup scenarios are easy or inexpensive because each is a unique engineering project of monumental proportions. Because of all the wreckage and the radiation danger, the Japanese must design, test, and build specialized tools, equipment, and even robots to do the cleanup work.

But before they can develop safe, cost-effective, realistic cleanup plans with definite goals and produce the tools they will need to do the work, they need to see inside the reactors so they can pinpoint exactly where the fuel is.

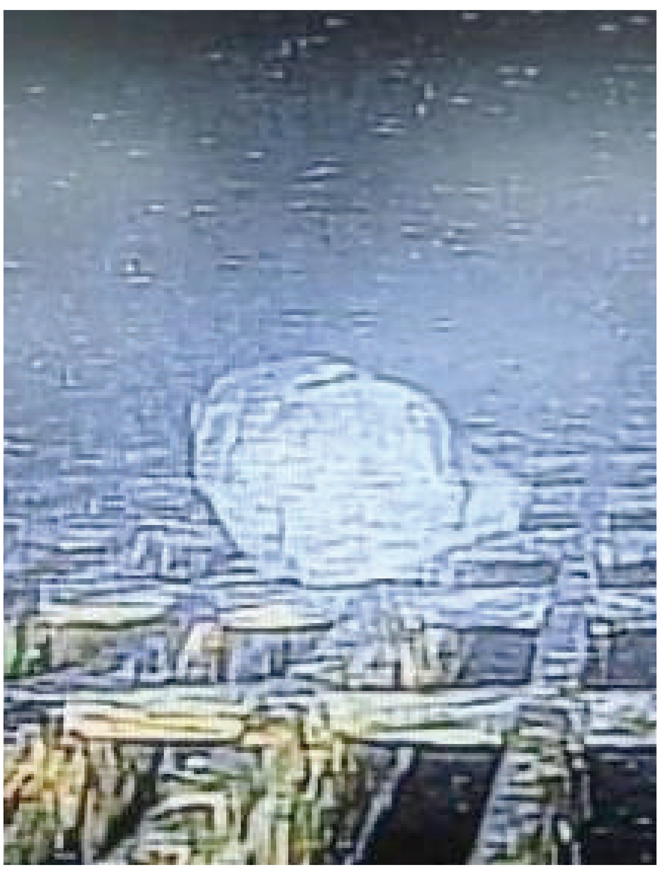
> **Because of all the wreckage and radiation, robots will be designed and built to do the cleanup work.**

Toshiba and the International Research Institute for Nuclear Decommissioning announced in June 2015 that they had developed a small motorized robot to investigate the primary containment vessel in Reactor 2. The robot will look along access routes for debris and fallen objects that might interfere with investigating the area. But the robot won't explore the reactor's core because Morris feels confident that the Laboratory's technology can provide that clear interior view. "Muon vision should allow experts to see, in three dimensions, how much of the nuclear material lies in what part of the reactors," Morris says. "Muon vision ought to give them the answers they so desperately need."

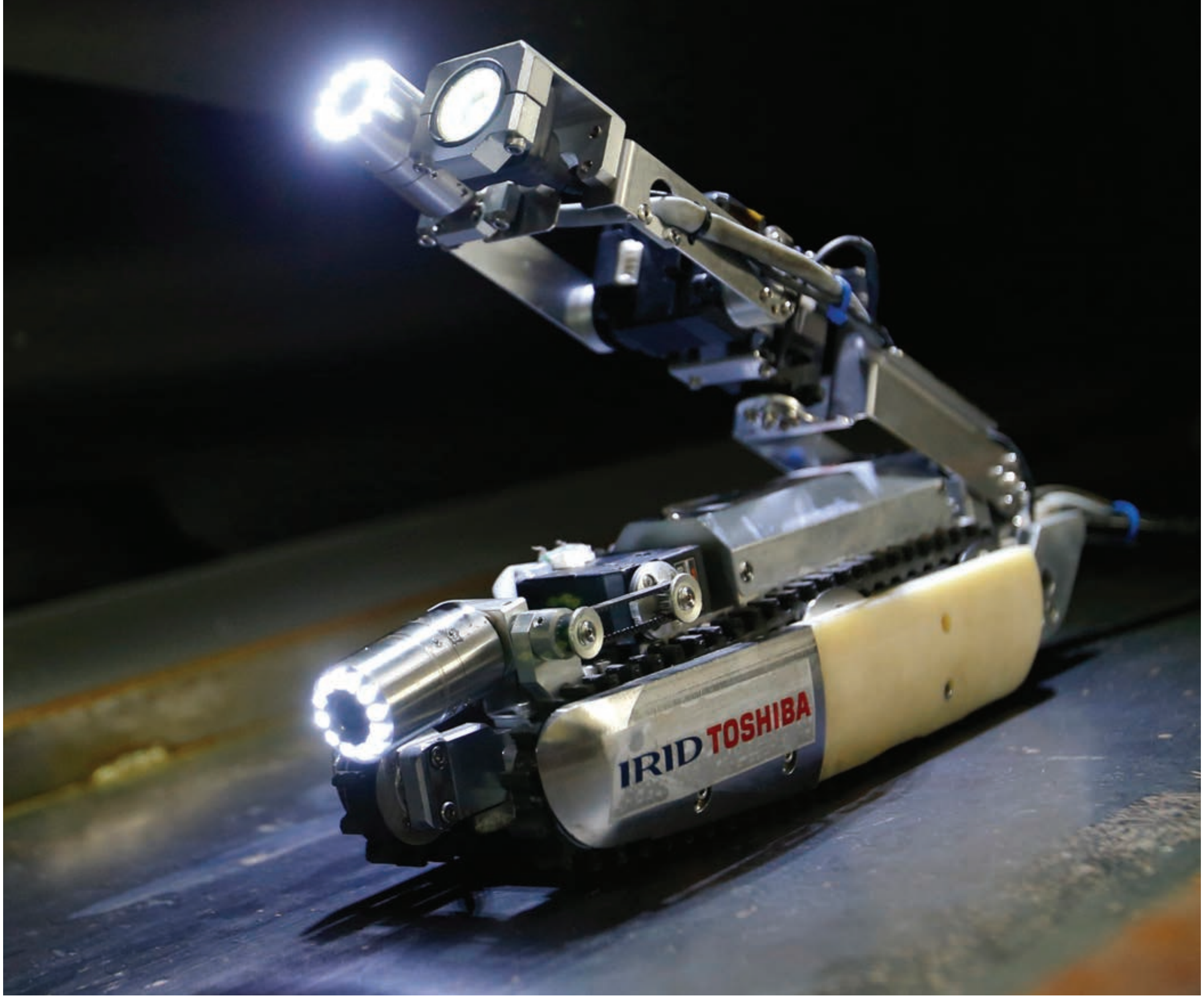
Seeing is believing

In the first days after the disaster, Morris and his team began considering muon vision's utility for Fukushima. Their rough computer simulations suggested that some muons were penetrating the hundreds of tons of concrete, steel, and nuclear fuel inside the crippled Fukushima reactors, but could those simulations be trusted?

To locate, identify, and determine the shape of nuclear materials, such as melted uranium fuel, inside a destroyed reactor, theoretically one has only to design a muon detection system large enough to see inside a reactor. Scaling up to reactor size, however, puts new requirements on the muon vision system. For instance, for a cargo container, the presence of nuclear materials can be ruled out in less than a



In April 2015, a small robot filmed the first images inside the PCV of Fukushima Reactor 1. Shown here are some of the debris it encountered inside the vessel. TEPCO reports that the robot recorded radiation levels of between 5 and 10 sieverts per hour (a tenth of what was expected) in some areas but levels as high as 25 sieverts per hour in others. A person receiving four sieverts in about one hour is at risk for death. (Photo: TEPCO)



Toshiba has developed the "scorpion" robot that raises its tail like a scorpion and collects data inside the primary containment vessel. The machine will help confirm whether robots can successfully navigate around debris. The robot, which is 21 inches long when extended, has two cameras, LED lighting, and a dosimeter. *(AP Photo/Shizuo Kambayashi)*

minute if there isn't significant scattering. If the scan reveals something heavy (such as uranium), a longer scan—enough to record many more muons—is needed to reveal the identity, location, and shape of the material.

The experiment proved that muon vision should work at Fukushima.

Morris and the team predicted that finding the fuel inside the Fukushima reactors would require the muon vision detectors to be in place for weeks or even months, recording as many muons as possible for a precise-enough reading to reveal the location and shape of the fuel. In theory, that approach should work, but Morris needed experimental confirmation. So his muon vision team constructed a simplified mock-up of a Fukushima-like reactor, substituting lead bricks for the uranium fuel. They offset the lead inside the reactor mock-up to represent the fuel having melted and moved, leaving an empty space.

The team realized, however, that the detectors could not be positioned as they normally are for interrogating cargo: above and below a container or truck to take advantage of the vertical path taken by most muons. (Trucks are simply driven through a structure whose floor and roof are muon detectors.) Such an arrangement would be impossible at Fukushima because a detector cannot be placed below a reactor. So the team arranged the detectors on either side of the reactor mock-up to record muons that were coming through it horizontally. Because fewer muons move horizontally—one-tenth the number that move vertically—the team ran the experiment nonstop for three weeks to get enough data, recording 100,000 muon tracks by the experiment's end.

Sure enough, the experiment produced a color 3D image of the lead and revealed the empty space left by the offset lead bricks. The experiment proved that muon vision should work at Fukushima.

Some engineers worried that there would not be enough horizontally scattered muons traveling through the reactors to make an image. They thought that the site's extremely high level of gamma-ray radiation (a result of the accident) would also be recorded by the detectors and overwhelm the detectors' ability to record the muons.

> **It would be a full hands-on, "no-smoke-and-mirrors" demonstration.**

The Los Alamos team went to Fukushima to find out whether a scaled-down muon detector would distinguish muons from the massive amounts of gamma-ray radiation. It did.

"The detector wasn't swamped by the gamma radiation at the site," Morris recalls. "It could still detect individual muons, in spite of being in that environment."

A big surprise

Toshiba became interested in pursuing Los Alamos's proposal. The Los Alamos team was invited to conduct a real-life test using real nuclear fuel on a real reactor—Toshiba's own research reactor. It would be a full hands-on, "no-smoke-and-mirrors" demonstration.

The Los Alamos team helped Toshiba arrange the muon vision system's two detectors on either side of the Toshiba reactor to record horizontally moving muons. Then, unbeknownst to the team, Toshiba's engineers installed two extra fuel assemblies. They also added blocks of steel and concrete outside the main fuel assembly's surrounding water vessel.

Toshiba wanted to blindly test muon vision's ability to see the reactor's fuel where it was not expected to be as well as through intervening walls and debris. Why? Because, if used at the devastated Fukushima site, the detectors could not be placed inside any of the reactor buildings. They would have to be outside but still be able to locate the fuel wherever it was on the inside.

> **"That's when we got the really big surprise: The extra fuel assemblies popped up in our images."** ~Chris Morris

Trusting that the test was set up properly, the Los Alamos team returned to the United States and left Toshiba's engineers to run the experiment. The Japanese collected data for a month before sending the results to Los Alamos for analysis. Los Alamos software constructed the muon tracks from the data, found the locations of scattered tracks, measured the scattering angles, and plotted the images.

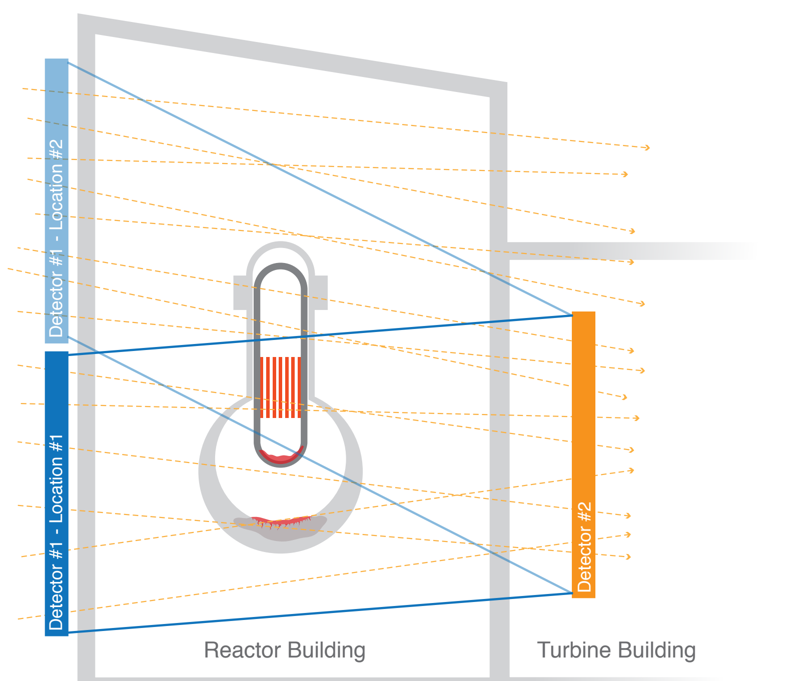
"And that's when we got the really big surprise: The extra fuel assemblies and blocks of steel and concrete blocks popped up in our images," Morris says. "We sent the images to Japan for review, and the once-doubtful Toshiba engineers were suitably impressed. Their extra components, meant to test our technique, were clearly visible in all the right places."

Muon vision in progress at Fukushima

A Japanese national project started in 2014 aimed at developing two muon detection systems that can be installed at Fukushima. Toshiba developed electronics that enabled operation of the muon detectors in the high-radiation environment and bought detector components from DSIC, and the Los Alamos team developed the algorithms needed to image the reactor. The designs of the electronics and firmware, and all the imaging work, will result from the collaboration between Los Alamos and Toshiba. The partners are working to design and build the two giant (24-feet-by-24-feet) muon detectors destined to scan Fukushima's Reactor 2.

> **"The Japanese are not going to let anything fall through the cracks."** ~Chris Morris

When the detectors are ready, Morris's team will go to Fukushima to help install them, debug the electronics, and test the signals. Los Alamos and DSIC will also provide software, system testing, and data analysis. The Japanese team



Muon vision will locate nuclear fuel using two giant muon detectors placed on opposite sides of the reactor buildings: one outside (blue) and the other inside the adjoining reactor's turbine building (orange). By changing the outside detector's position, researchers can determine how much fuel is in the lower portions of the pressure vessel and the containment vessel and how much of the reactor core might still be intact.

These 24-feet-by-24-feet muon detectors (one above and one behind the man addressing the crowd) will be used at the Fukushima Daiichi nuclear power plant to locate nuclear-fuel debris inside the plant's destroyed nuclear reactors. Los Alamos developed muon vision technology. *(Photo: Kyodo via AP Images)*

will execute the actual measurements at Reactor 2. To get the best-possible image, data will be collected for at least six months.

A vice president of Toshiba Corporation Energy Systems & Solutions Company speaks highly of the project. "All of us at Toshiba are pleased to have worked with [Los Alamos] on development of this technology," he says. "We are confident that it will prove to be a useful tool for analyzing the interior of the [reactor pressure vessel]."

Morris agrees. "The Japanese are not going to let anything fall through the cracks," he says. "We have met with them every week since last summer, testing, refining, and perfecting to make sure this works."

Using muon vision, they hope to locate the fuel in Reactor 2 before 2018. The appropriate robots and other equipment needed for the cleanup should be ready by 2020.

How important is the cleanup?

The plan is to recover as much radioactive material as possible and reclaim the land. At stake are Japan's reputation, its public health, and the health of its environment.

Also at risk is the future of Japan's nuclear industry. Before the Fukushima disaster, nuclear energy provided 30 percent of Japan's electricity, making nuclear energy a mainstay of the country's economy. After the accident, public concern about nuclear-power safety in a country prone to earthquakes led to the shutdown of the country's 48 remaining nuclear reactors.

Since the disaster, electric energy shortages have brought hardships and slowed Japan's economic output. In addition, the cost of producing electricity has increased by 20 percent. The Japanese government estimates that its power companies paid $29.6 billion more in fuel costs in 2013 than in 2010, the year before the Fukushima disaster. The main reason for the increase is Japan's greater need for imported fossil fuels to generate electric power. Japan was already importing 84 percent of its energy before the disaster.

The country's greater reliance on imported fuel has increased Japan's concerns about its energy security and its national security, so the Japanese are considering restarting some of the 48 nuclear power plants they closed. The government, TEPCO, and the Japanese nuclear industry hope the full cleanup of Fukushima will help rebuild public acceptance of nuclear power.

> **"The arc of Los Alamos's history with Japan is truly awesome."** ~Chris Morris

"The work required for this cleanup project is complex and dangerous, and muon vision may be important to its success," Morris says. "We'll be helping to solve one of the biggest environmental cleanup problems in the world."

"And you know what else is amazing?" he continues. "It was Los Alamos that ushered in the nuclear age. Since then, the Japanese have embraced nuclear technology as being fundamental to their energy and national security. That security is threatened by the Fukushima disaster, and now the Laboratory is going to help them dig out from under it. The arc of Los Alamos's history with Japan is truly awesome."

~Necia Grant Cooper

The Los Alamos Muon Radiography team visited the damaged Fukushima Daiichi reactor complex to evaluate whether Los Alamos's scattering method for cosmic-ray radiography could be used to image the location of nuclear materials within the reactor buildings. (Photo: Los Alamos)